Simulation of sudden stratospheric warmings with the Middle and Upper Atmosphere Model

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Abstract

The Middle and Upper Atmosphere Model has been used to simulate the middle atmosphere variability by changing the lower boundary conditions. For this purpose quasi steady-state simulations were performed for individual days around the sudden stratospheric warmings (SSWs) in January 2009 and 2012. The modelled time series reveal a qualitatively good agreement with reanalysis zonal wind with the observed one by reanalysis at the same height and latitude. A medium-range prediction of SSW events appears possible if planetary waves (PW) in the lower stratosphere are additionally assimilated in form of externally forced travelling PW.

Zusammenfassung

Mit dem Modell der mittleren und oberen Atmosphäre ist der Einfluss der unteren Randbedingungen auf die Variabilität der mitteren Atmosphäre simuliert worden. Dafür wurden eine Vielzahl quasi-stationärer Modellläufe durchgeführt, die in ihrer Gesamtheit den zeitlichen Verlauf der plötzlichen Stratosphärenerwärmungen im Januar 2009 und 2012 wiedergeben. Es zeigt sich, dass der modellierte mittlere Zonalwind in qualitativ guter Übereinstimmung zu den Reanalysen liegt. Bei einer zusätzlichen Assimilation stratosphärischer planetarer Wellen wäre eine Mittelfristvorhersage für stratosphärische Erwärmungen möglich.

1. Introduction

The circulation of the atmosphere also includes the thermosphere/ionosphere system. Through vertical coupling processes by upward propagating small scale gravity waves (GW) with high phase speeds (e.g., Fritts and Vadas, 2008), global wave structures such as planetary waves (e.g., Borries and Hoffmann, 2010; Mukhtarov et al., 2010; Hoffmann et al., 2011) or even more irregular phenomena (e.g., sudden stratospheric warmings; SSWs) may be transferred into the upper atmosphere (e.g., Goncharenko et al., 2010). Usually, a direct impact is not possible due to the wind reversal in the mesosphere/lower thermosphere (MLT) region. Because standard reanalysis products, e.g., ECMWF and MetOffice (Swinbank and Ortland, 2003), provide only data up to the lower mesosphere ($\sim$ 60 km) satellite measurements, e.g., from TIMED (`http://www.timed.jhuapl.edu/WWW/index.php`) and model results help to extend the picture up to the thermosphere. Until now, there exists no comprehensive database to investigate the signals of the middle atmosphere in a changing climate.
In order to simulate the so-called "meteorological" influence on the thermosphere, whole atmosphere circulation models, for example, HAMMONIA[1] (Schmidt and Brasseur, 2006),

[1] HAMburg Model of the Neutral and Ionized Atmosphere

WAM[2](Wang et al., 2011), and TIME-GCM[3](Roble and Ridley, 1994), can be used to reproduce the observed phenomena in the stratosphere (SSW, PW) first. The response of the middle and upper atmosphere can be studied next.
Here, we simulate quasi steady-state conditions with MUAM[4] (Pogoreltsev et al., 2007) for each day around the SSW in January 2009 and 2012 by changing the lower boundary conditions (zonal mean temperature and stationary planetary waves). These are taken from NCEP reanalysis (Kalnay et al., 1996).
In according to Kuroda (2008), which declare the role of the stratospheric polar vortex on the quality of seasonal forecasts, a potential medium-range prediction of SSW events (30 days) will be proposed by running small ensemble simulations (6 members) with slightly different amplitudes of externally forced travelling PW components.

2. Nature of sudden stratospheric warmings

The state of the polar winter circulation in the stratosphere/mesosphere is more disturbed than on the summer hemisphere due to the global distribution of PW and their interaction with the mean flow. An intensification of these global scale waves, which are predominantly stationary and westward propagating, lead to momentum deposition, an oscillating state, and a non-zonal symmetric structure of the background winds (e.g., Haynes, 2005). So-called sudden stratospheric warmings (SSW) are the consequence of the polar vortex breakdown. The preconditions of SSW in the troposphere has been recently studied by Cohen and Jones (2011). They found that sea-level pressure anomalies over the north Atlantic and north Pacific (Arctic Oscillation) that influence the Siberian high may be responsible for an intensified upward energy flux. This oscillating state of the background flow continues for one or two weeks and impede the vertical propagation of PW into the mesosphere. Instead of that, a reflexion of the wave occur that leads to a downward interaction between stratosphere and troposphere (e.g., Reichler et al., 2005; Kodera et al., 2008; Hinssen et al., 2011).

Recently, a major stratospheric warming in January 2012 caused cold weeks at the end of that month up to about mid February over Siberia and Central and Eastern Europe as well. Such behaviour is a typically feedback of the tropospheric circulation on SSW at midlatitudes (e.g., Limasuvan et al., 2004; Mukougawa et al., 2005; Mukougawa and Hirooka, 2007; Hirooka et al., 2007). Figure 1 illustrates a troposphere-stratosphere-troposphere cycle around a SSW event. Reichler et al. (2005) divides the life-time in five stages: (1) forcing of PW, (2) upward-propagation, (3) wave breaking, (4) downward-propagation and (5) tropospheric feedback. This leads to weaker tropospheric westerlies associated with more defined blocking patterns (e.g. Schoeberl, 1978; Labitzke, 1981; Hinssen et al., 2011) in the North Atlantic Oscillation (NAO). However, the nature of trigger mechanisms (e.g. tropical convections) that cause such phenomena is not still completely understood.
Especially, the role of the middle atmosphere in the future climate and the change of SSW in frequency and intensity will be an important question to answer. Currently, climate models (e.g. ECHAM5) do not really include middle atmosphere dynamics (note, however, that the recent ECHAM6 model includes a more detailed middle atmosphere). Generally,

[2]Whole Atmosphere Model
[3]Thermosphere- Ionosphere-Mesosphere-Electrodynamics general circulation model
[4]Middle and Upper Atmosphere Model

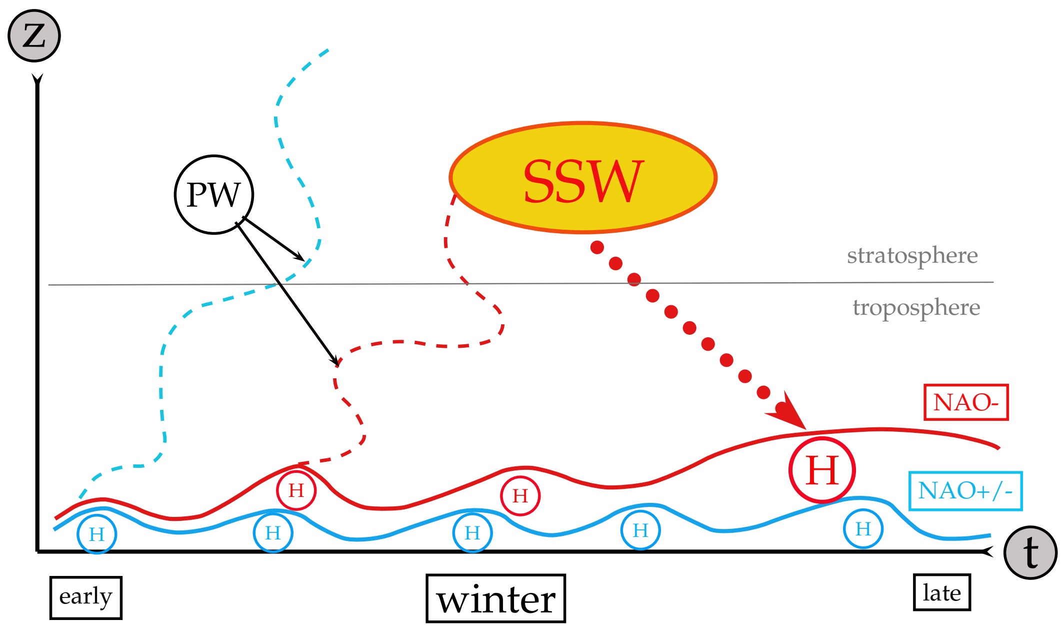

Figure 1: *Scheme of the troposphere-stratosphere-troposphere interaction during sudden stratospheric warming (SSW) events after Reichler et al. (2005).*

climate models underestimate the feedback of the stratosphere to the troposphere during SSW events.

3. Model setup

The mechanistic circulation model MUAM was operated in the following configurations. The simulations start with a windless atmosphere and stationary waves are forced by the lower boundary conditions (daily NCEP fields). During the "warm-up" process (0-120 model days) the atmospheric circulation develops under steady-state conditions (e.g., monthly mean ozone climatology). After 30 days the model Earth begins to rotate and tidal waves are excited due to the ozone absorption in the lower stratosphere. Finally, the model results from days 120-150 are averaged and the obtained middle atmosphere circulation (up to 130 km) corresponds to the day that is used as lower boundary condition.
Altogether 89 simulations (from 2008-12-01 to 2009-02-28) has been performed automatically in order to simulate the conditions around the SSW event in January 2009. During the runs the declination angle of the sun and the monthly ozone distribution is set in accordance to the respective day. Other than in previous simulations with MUAM (e.g. Pogoreltsev et al., 2007; Hoffmann and Jacobi, 2011) the most important parameters have been defined as namelist in order to modify these without recompile the model code. In Tab.1 we summarize some technical information about the running system. By starting simulations on 2008-12-01 with the model "warm-up" (CPU time ca. 1.5h) one obtains a quasi "steady state" 0.5h later. These 30 days of model results are saved and converted into *netcdf* format. The temporal average represents the conditions for the particular day and is calculated later by external analysis software. The following days are modelled by replacing the lower boundary conditions. After further 30 model days (0.5h) the new state is obtained. This saves CPU time because the assimilation of the new data starts from the previous tuned model state. Accordingly, a 3-month season simulation takes about 2 days of CPU time on one server and one cluster. The obtained data require about 62

GByte disk space.
Ensemble simulations with a sufficiently large number of runs per day (e.g., 40) enable additional application for such models for a potentially seasonal forecast.

simulations	**"warm-up"**	**"steady state"**	**"state change"**
			change LB
model days	0-90 d	90-120 d	120-150 d
CPU-time	1.5 h	0.5 h	0.5 h
space into Netcdf format	not saved	683.4 MByte	683.4 MByte

	2008-12-01	**2008-12-02 to 2009-02-28**	total
"warm-up"	1	0	1
"steady state"	1	0	1
"state change"	1	88	89
CPU-time / h	2	44	$<$ 2 days
disk-space / GByte	0.6834	60.8226	$\sim$ 62

Table 1: *List of technical parameters related to ensemble simulations with MUAM on compute-servers at LIM.*

4. Simulation of SSW in January 2009

In this section we describe the simulation results by only replacing the lower boundary conditions for the day 2009-01-010 (before SSW) and 2009-01-20 (during SSW). For the two situations the modelled mean zonal wind, stationary planetary waves and the Eliassen-Palm-flux divergence is discussed. Finally, the course of the 89 simulations from 2008-12-01 to 2009-02-28 are compared with NCEP reanalysis data ($\sim$30km).

4.1 Lower Boundary Conditions

Information about the real atmosphere are taken from NCEP reanalysis data. The spectral components of the first 3 zonal harmonics in temperature and geopotential height were extracted from the 1000hPa pressure level as well as the zonal mean temperature distribution up to about 30km. The latitudinal distributions of these parameters are depicted in Fig.2. This corresponds to the global distribution of high (positive) and low (negative) geopotential height shown in Fig.3.

2009-01-10 (before SSW)

On the northern winter hemisphere the amplitude distribution (Fig.2, left panel, top) for the zonal wavenumber 1-3 indicates a dominant maximum of wave 1 (solid) at 60°N

($A_{W1} = 170m$). Quasi stationary waves with shorter horizontal wavelength are weaker. At lower midlatitudes (∼40°N) the amplitude of wave 1 decreases below the one of wave 2 and 3 (dashed, dotted). On the global map in Fig.3 (left panel) the longitudinal distribution of geopotential height around 60°N reveals high geopotential (pressure) over the continents (Siberia) and low geopotential (pressure) over the north Atlantic ocean. At midlatitudes we observe a superposition of wave 2 and 3 mainly caused by the land-sea contrast there. Also local synoptical disturbances (high over Central Europe) that are usually reduced by averaging over one month are visible considering daily values. These may be responsible to trigger SSW events.

2009-01-20 (after SSW)

A few days later the amplitude distribution changes dramatically. Figure 2 (right panel, top) shows that wave 2 achieves almost the same magnitude as wave 1 has. Due to the strong pressure gradient over the north Atlantic (negative NAO index) it develops two cells with high geopotential; one over north east Siberia and another one over Aleuts. In transition of the two states on 2009-01-15 wave 2 and 3 dominates at midlatitudes (40°N-60°N) with similar amplitude of about $A_{W2} \backsimeq A_{W3} \backsimeq 130m$. The positions of the maxima (not shown here) are slightly shifted with 40°N (W2) and 50°N (W3).

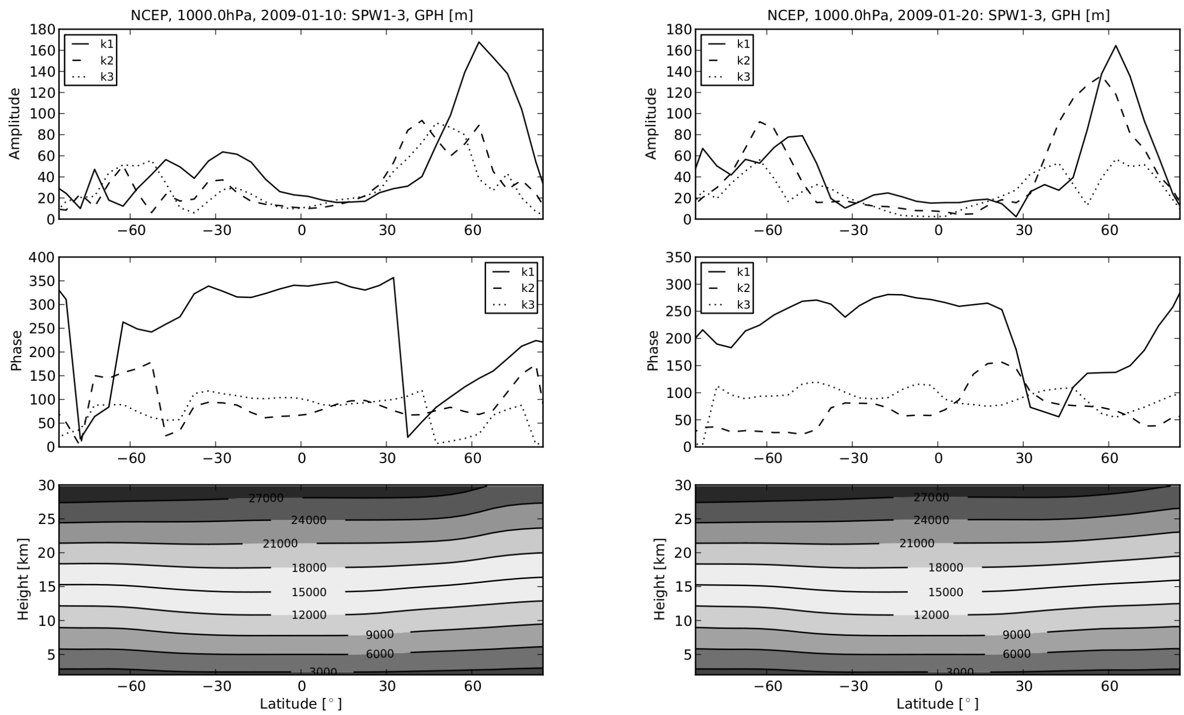

Figure 2: *Latitudinal distribution of amplitude (upper) and phase (middle) of the first three zonal harmonics in geopotential height at 1000 hPa on 2009-01-10 (left) and 2009-01-20 (right). The lower panels show cross setions of the zonal mean geopotential height.*

4.2 Wave-mean flow interaction

The model simulations for the previously discussed lower boundary conditions are shown in this subsection. Thereby, we focus on the northern hemisphere. The most prominent

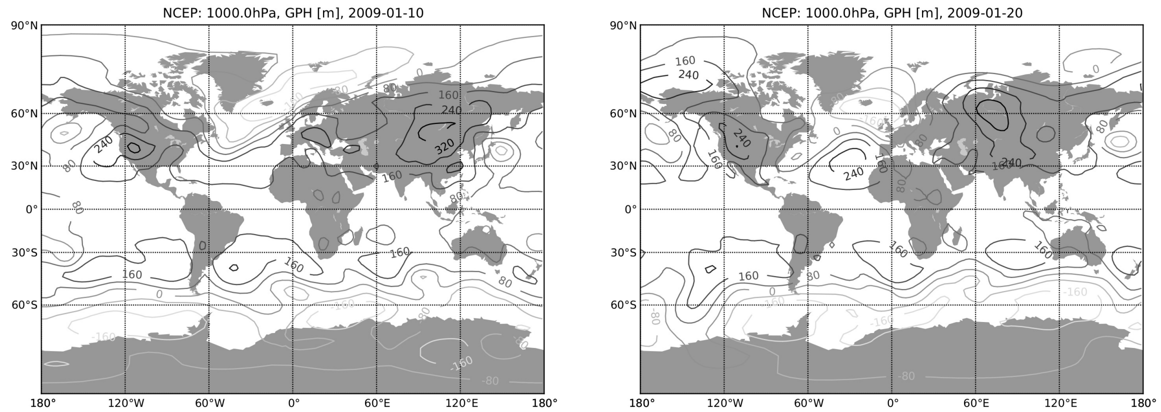

Figure 3: *Maps of geopotential height distribution at 1000 hPa pressure level on 2009-01-10 (left) and 2009-01-20 (right).*

wave features in the middle atmosphere are stationary planetary waves (SPW). These are forced in the troposphere (distribution of continents) and propagate upward during westerly wind regimes on the winter hemisphere. Because our simulation base on daily initial data they result in a strong variation of SPW. Figure 4 presents height-latitude cross sections of SPW1-3 amplitudes for the days 2009-01-10 (upper row) and 2009-01-20 (lower row). In according to the amplitude distribution as provided by the lower boundary conditions (see Fig.2) the SPW1 show the strongest magnitude of about 18K before SSW. 10-days later the pattern reverse. On 2009-01-20 (during SSW) SPW2 dominates (12K) and SPW1 reaches only about 6K. The amplitude of SPW3 changes from 4K to 2K. How far this component has an impact on SSW is unclear.

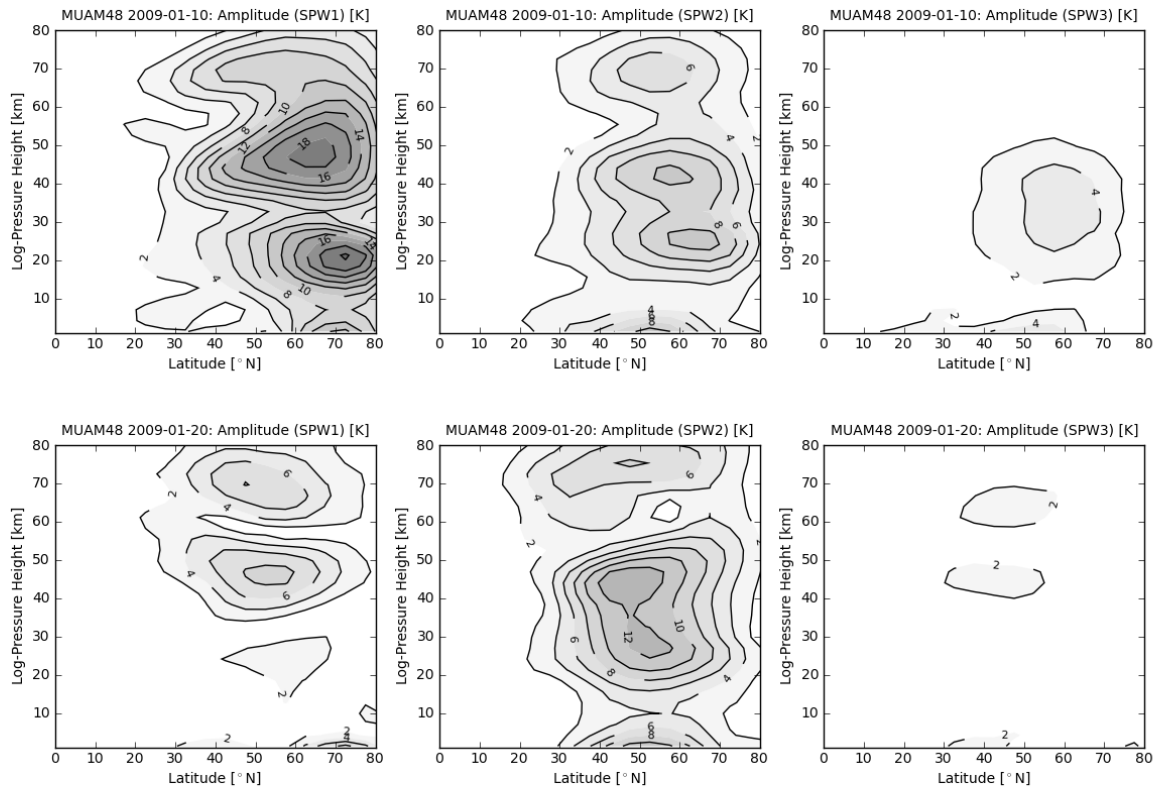

Figure 4: *Height-latitude cross section of SPW amplitude simulated with MUAM using the daily lower boundary conditions 2009-01-10 (upper row) and 2009-01-20 (lower row): SPW1 (left), SPW2 (middle) and SPW3 (right).*

This wave characteristics is a signature of the SSW itself.

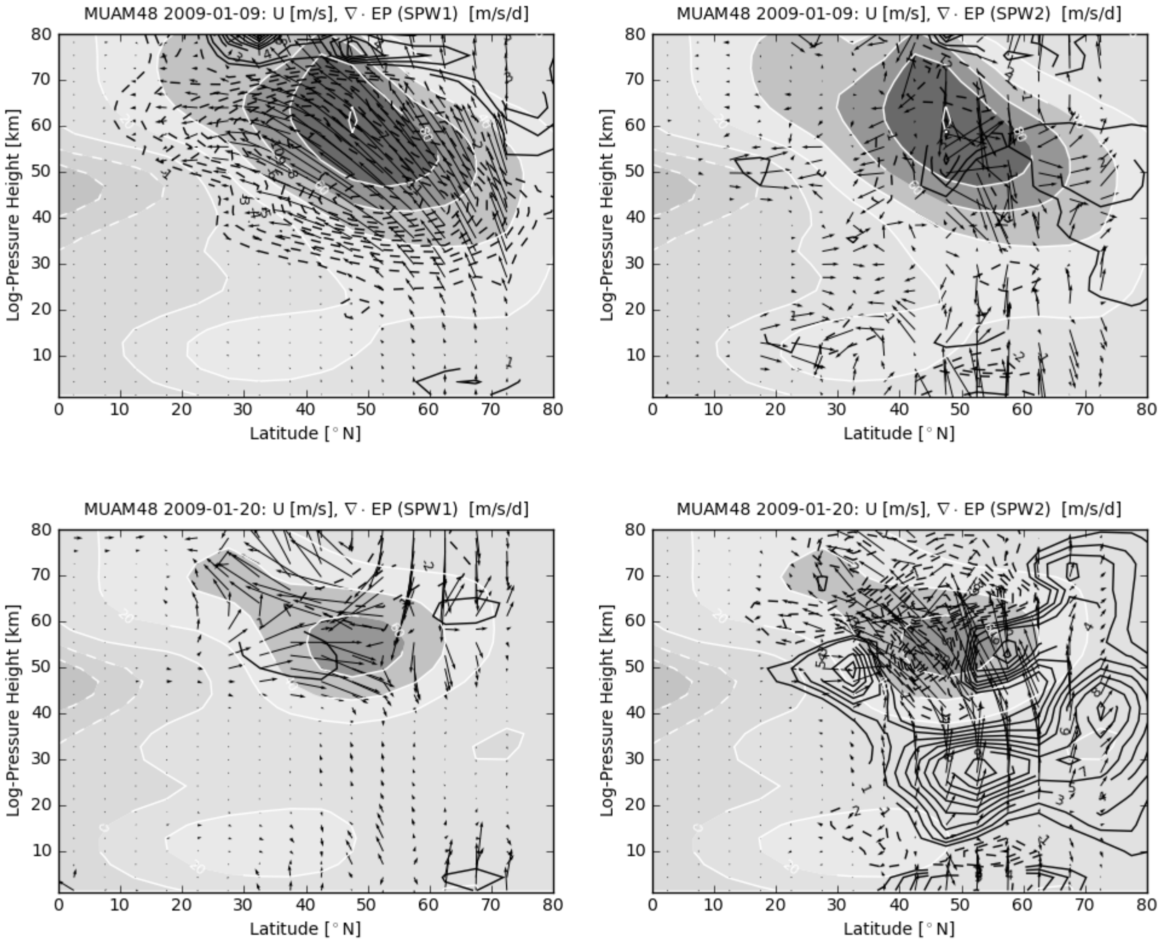

Figure 5: *Height-latitude cross section of Eliassen-Palm Flux (arrows) divergence (black contours) of SPW1 (left) and SPW2 (right) simulated with MUAM using the daily lower boundary conditions 2009-01-10 (upper row) and 2009-01-20 (lower row). The mean zonal wind is given in greyscaling, respectively.*

4.3 NCEP-MUAM comparison

The north-polar projection of the geopotential height distribution (Fig.6) near 30km reveals the dramatic breakdown of the polar vortex within a few days. The upper row represents MUAM simulation results for the two dates. The lower row shows the NCEP data, respectively. In both cases the polar vortex is deep and undisturbed on 2009-01-10 and weak and strongly disturbed on 2009-01-20, even though the bipolar structure is not full reconstructed with the model. This is well-explained by the absence of travelling PW. During the warming PW at high latitudes are reflected at the easterly wind jet.

A temporally resolved picture is obtained by collecting all 89 MUAM runs to reproduce the atmosphere circulation around the SSW event in January 2009. Figure 7 (lower row) depicts the course of the single simulations (circles) from 2008-12-01 to 2009-02-28 in comparison to the NCEP data (solid line) at 62.5°N/30km for mean zonal wind (left panel)

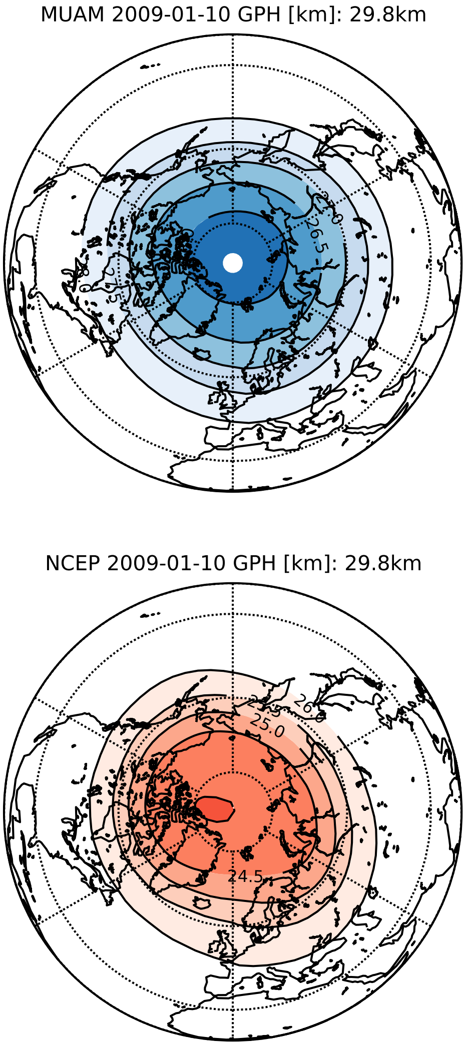

Figure 6: *North-polar projection of geopotential height near 30km in MUAM (upper row) and NCEP (lower row) for 2009-01-10 (left column) and 2009-01-30 (right column).*

and temperature (right panel). On 2009-01-10 the circulation begins to change abruptly. The mean zonal wind decreases within the following 20 days from $55m/s$ to $-15m/s$. This is accompanied with a temperature increase of about $30K$. MUAM simulations are able to reproduce such tendencies in winds quite well, even though the temperature increase only amounts to $12K$. Especially, the warming episode around 2009-01-30 is underestimated and the precondition of the warming indicates an offset of about $-5K$. This results in a much to weak zonal wind reversal. Thus, the assimilation of externally forced travelling PW is necessary to improve the precision of the simulation. They import extra energy and momentum into the system and will rise the mean temperature and reinforce the wind reversal. From this example we can see that the temperature response of the dynamical development follows with a delay of circa 10 days. However, a time shift between the MUAM simulations and NCEP reanalysis is not visible as expected.
The modelled response of the MLT region to the assimilated SSW in the lower stratosphere is depicted in the Fig.7 (upper row). At an approximated height of about 100km (log-pressure height) the zonal wind values are consistently negative (easterly). The pre-

condition is characterized by a strong oscillating state of the background wind and temperature. With the onset of the decreasing zonal wind at 30km, a shortly continuing wind jump from -20m/s to 35m/s and back reveals the vertical coupling over more than 50km, quasi simultaneously. This shows the relevance of SSWs and PW on the dynamics of the upper atmosphere.

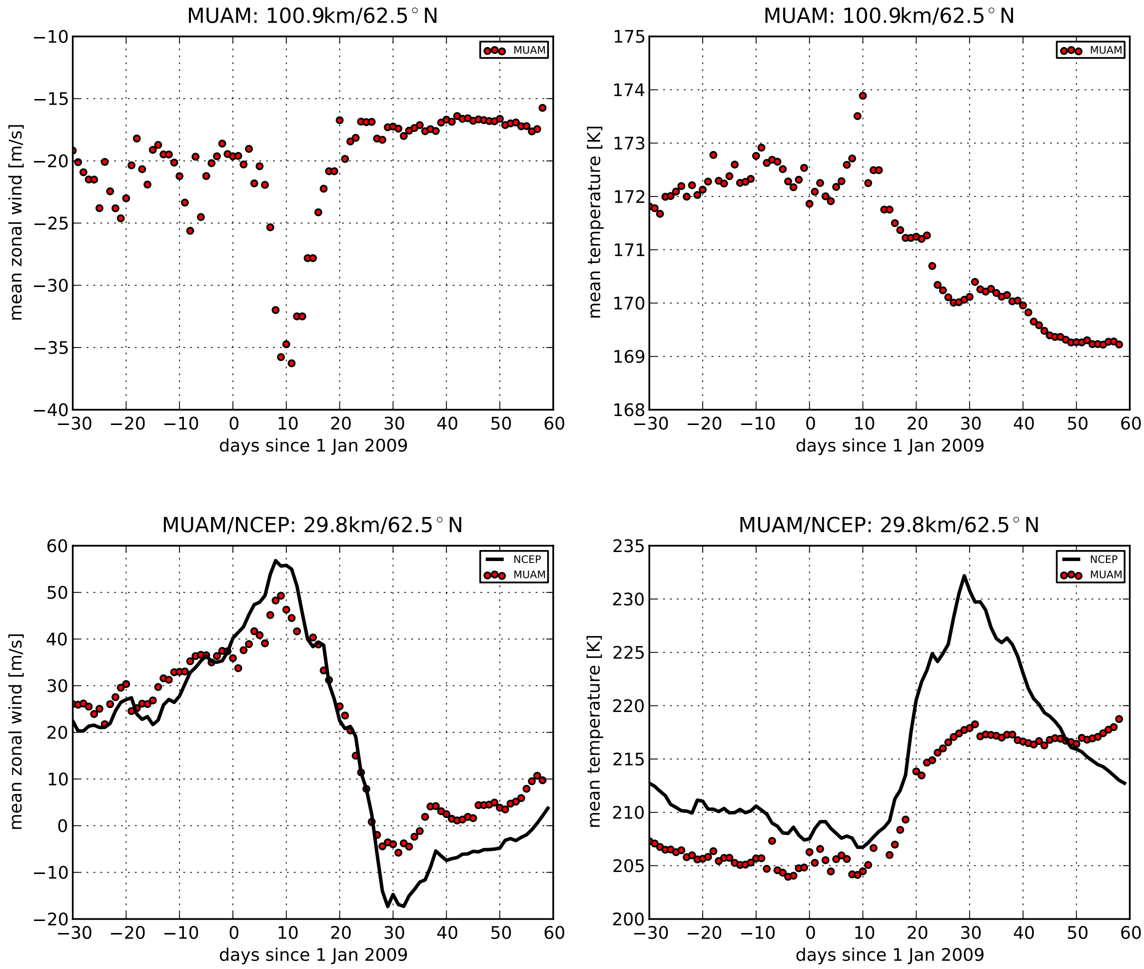

Figure 7: *Comparison of mean zonal wind (left) and mean temperature (right) at 62.5°N/30km between NCEP reanalyses (heavy black line) and MUAM simulations (circles) from 2008-12-01 to 2009-02-28 (lower row). The modelled time series at 100km, respectively (upper row).*

The importance of the traveling PW forcing in the model is evident in Figure 8 (right panel). It presents one ensemble simulation for the date 2009-01-06. Because the real information of traveling PW are not considered and assimilated to this point, the amplitude of the quasi 16-day wave has been gradually increased (see Table in Fig.8) in order to improve the temperature simulation. The results of the 6 simulations reveal one single member with a 60% stronger amplitude that is able to predict the temperature jumps in near future quite well. In the other simulations temperatures remain below the observations. Only a resonant configuration of externally forced PW provides the breakdown of the polar vortex. Consequently, ensemble means are not helpful, but each member must be individually considered. In order to improve the predictability of SSW events the full spectrum of PW obtained from reanalyses must be assimilated. Additional simulations per ensemble could increase the probability to find the correct configuration.

PW mode	**16DW (1,3)**	**10DW (1,2)**	**5DW (1,2)**	**4DW (2,1)**
PW1111	0.500E-4	0.37E-4	0.20E-4	0.55E-4
PW2111	0.600E-4	0.37E-4	0.20E-4	0.55E-4
PW3111	0.700E-4	0.37E-4	0.20E-4	0.55E-4
PW4111	0.800E-4	0.37E-4	0.20E-4	0.55E-4
PW4111	0.900E-4	0.37E-4	0.20E-4	0.55E-4
PW5111	1.000E-4	0.37E-4	0.20E-4	0.55E-4

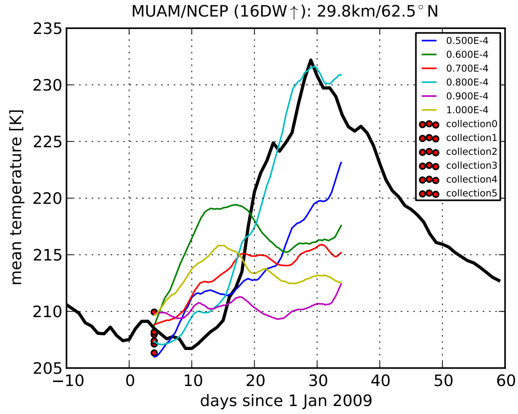

Figure 8: *Example medium-range forecast (30-days) on 2009-01-04 for mean temperature (right) before SSW by changing the amplitude of the externally forced 16-day PW. The table of the used amplitudes of externally forced PW is given on the left.*

One additional model experiment has been carried out for the recent SSW in January 2012. Equivalent to Fig.7, Fig.9 shows the MUAM (circles) and NCEP (solid line) time series from 2011-01-01 to 2012-01-31. Different from the previously discussed example, the warming in late January is accompanied by the zonal wind change at 62.5°N within a few days from $35m/s$ to $10m/s$. The oscillating behaviour of the mean zonal wind in December 2011 is caused by interaction with PW. These are currently not explicitly forced in the performed MUAM simulations. Consequently, the precondition of the warming is not exactly represented in the model. However, the general tendency of the mean zonal wind and temperature can be simulated with the model.

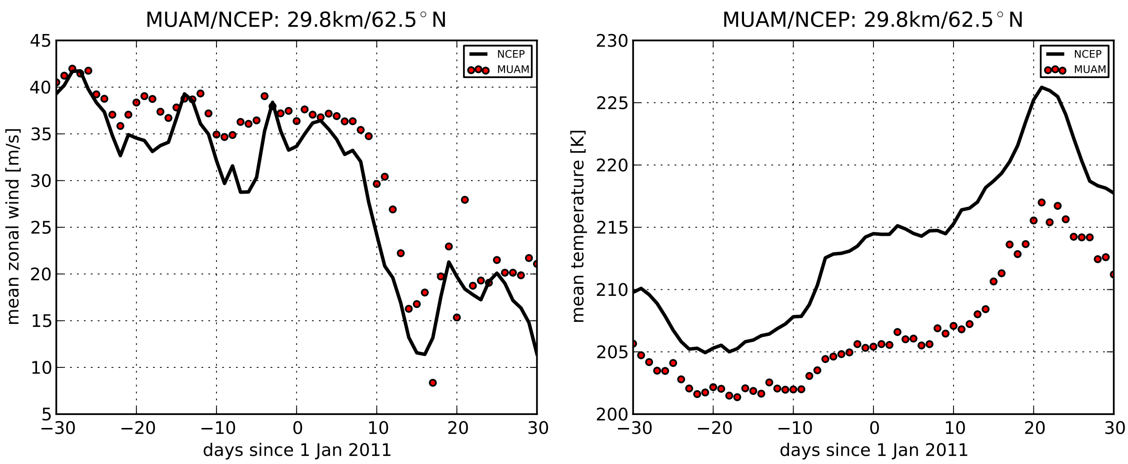

Figure 9: *Comparison of zonal standard deviation in zonal wind (left) and temperature (right) at 62.5°N/30km between NCEP reanalyses (heavy black line) and MUAM simulations (circles) from 2011-12-01 to 2012-01-31.*

5. Conclusions and Outlook

The application of mechanistic circulation models of the middle and upper atmosphere is actually underestimated and in the past, these are only used for studies with the focus on wave propagation and to simulate their consequence of the background and non-linear interactions. The *upper atmosphere research group* at Leipzig Institute of Meteorology (LIM) works on an extended application of this model family in order to investigate the sensitivity of the middle atmosphere in a changing climate on the on hand and to apply such models for quasi real-time simulations up to the upper atmosphere (∼400km) on the other hand. Within and acceptable time-fame ensemble simulations can be operated.
This is demonstrated by a simulation of the SSW in January 2009. MUAM is able to reproduce such stratospheric characteristics by a lot of composed single simulations each with a new lower boundary condition, respectively. These provide additional information up to the thermosphere. The predictability of SSW and PW activity and their response to the upper atmosphere will be the most important application in the future.
The performed simulations have shown that MUAM is able to qualitatively reproduce SSW without the assimilation of externally forced travelling PW in the stratosphere, when mean zonal fields are assimilated in the troposphere. However, PW forcing is necessary in order to predict the middle atmosphere circulation more accurate and to extend and tune MUAM for further applications.

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